

# FINAL TECHNICAL REPORT

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## Laboratory earthquakes along interfaces with rock gouge

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### Abstract

Studies of dynamic ruptures in our highly instrumented experimental setup have addressed a number of important issues in earthquake dynamics, confirming the possibility of supershear transition, demonstrating the change of rupture mode from crack-like to pulse-like with decreasing fault prestress, investigating the importance of the bimaterial effect, and studying off-fault attenuation and damage.

So far, these laboratory studies have been conducted on analog materials such as Homalite. A linear elastic material under the strain rates of interest, Homalite has wave-mediated stress transfer through the bulk qualitatively similar to rocks while the experiments feature slip rates similar to those encountered in the field. Furthermore, a significantly (~20 times) lower shear modulus of Homalite is an important experimental advantage, since it significantly decreases all relevant critical length scales, such as the critical crack size and nucleation size, allowing us to study well-developed shear ruptures in well-controlled and well-instrumented samples of tens of centimeters, instead of several meters as would be required for rocks. However, Homalite interfaces may have different evolution of friction properties from rock ones, due to differences in thermal, microstructural, chemical, and other properties.

In this award we have studied rupture dynamics with rock-governed frictional resistance by incorporating rock gouge into the Homalite sample interfaces, as mm-wide layers embedded into a part of the interface. This combination has allowed us to retain the advantage in reduced length scales offered by bulk Homalite, while permitting us to study dynamic rupture phenomena on interfaces more relevant to earthquake phenomena as well as to interrogate the evolving friction of rock gouge due to slip-rate regimes characteristic of dynamic rupture.

Using our newly developed technique to image full-field dynamic ruptures, we have started to explore rupture behavior on interfaces with rock gouge. In particular, one aspect that we have focused on is whether the rock-gouge interfaces exhibit the pulse-like to crack-like rupture mode change with increasing prestress, as observed in Homalite. Since flash heating in rocks has been shown to reduce the asymptotic dynamic values of the friction coefficient even more than in Homalite, to values of ~0.1-0.2 (Goldsby and Tullis, 2011), we would expect that the interfaces with rock gouge would produce pulse-like ruptures for even lower shear prestresses than the Homalite interfaces. Indeed our initial experimental observations have shown the crack-like to pulse-like transition for the rock-gouge interfaces.

We have also developed a new approach to study the evolution of the gouge interface with slip by producing multiple ruptures along the same gouge interface. An important finding is that repeated ruptures result in more dynamic weakening of the gouge interface compared to Homalite. The dynamic friction along a gouge interface drops to levels that are consistent with the measurements of Goldsby and Tullis (2011).

From a more general point of view, this study has advanced our understanding of rupture dynamics and types of frictional behavior relevant to fault slip, thus contributing to reduction of losses from earthquakes in the US. The developed experimental capability with rock-gouge interfaces will also significantly enhance our nascent study of the effect of fluid injection on rupture initiation and propagation.

## **Publications and presentations supported by this project:**

- Rubino, V., A.J. Rosakis and N. Lapusta, Understanding dynamic friction through spontaneously evolving laboratory earthquakes, *Nature Communication*, in press, 2017.
- Rubino, V., A.J. Rosakis and N. Lapusta, Laboratory earthquakes along interfaces with rock gouge, manuscript in preparation, 2017.
- Rosakis, A.J., N. Lapusta, and V. Rubino, Using laboratory earthquake ruptures to reveal the structure of dynamic friction, *ASCE-EMI Conference*, San Diego, CA, June 4-7, 2017.
- Rosakis, A.J., N. Lapusta, and V. Rubino, Dynamic imaging of spontaneously evolving friction in laboratory earthquakes, *AGU Fall Meeting*, San Francisco, CA, December 12-16, 2016.
- Rubino, V., A. J. Rosakis, and N. Lapusta, Dynamic friction measurements using ultra-high-speed digital image correlation in laboratory earthquake ruptures, *iDIC Conference and Workshop/SEM Fall Conference*, Philadelphia, PA, November 7-10, 2016.
- Rubino, V., A. J. Rosakis, and N. Lapusta, Dynamic visualization of supershear ruptures, *XXIV ICTAM*, Montreal, Canada, August 21-26, 2016.

## **Developing our laboratory earthquake setup to enable full-field imaging of dynamic ruptures**

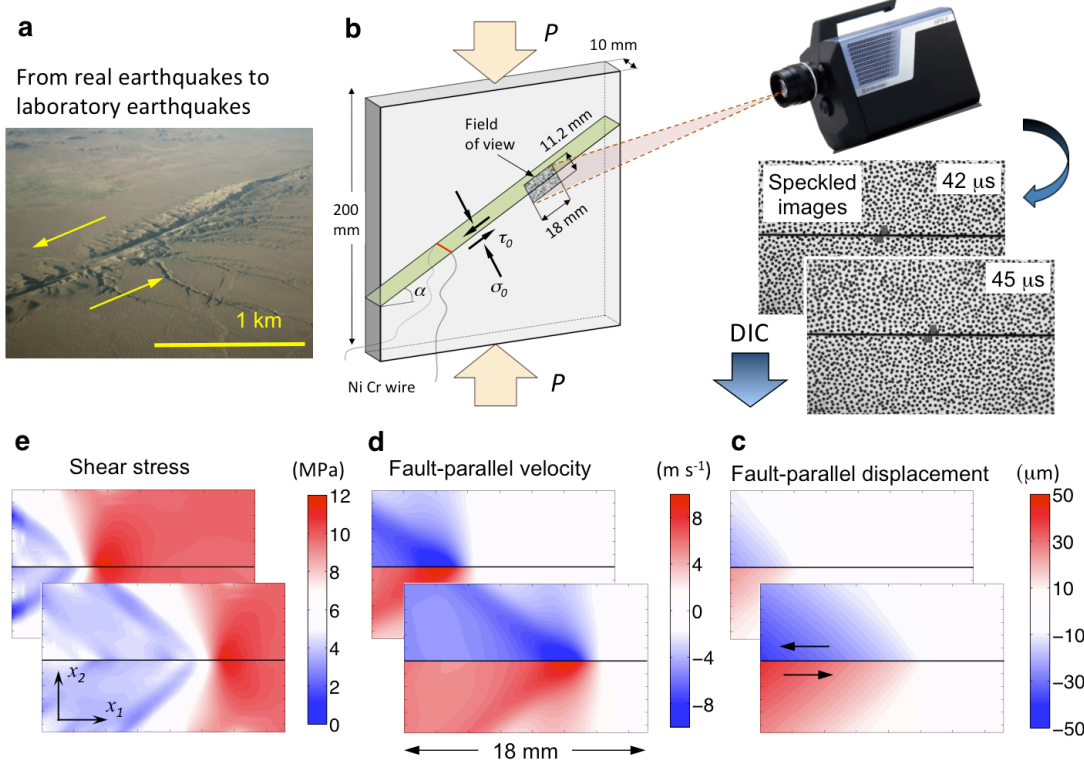
Our previous version of laboratory earthquake setup has been successfully employed to study a number of key dynamic rupture phenomena, including supershear transition, bimaterial effect, and off-fault attenuation and damage (Rosakis et al., 1999; Rosakis, 2002; Xia et al. 2004; Xia et al., 2005; Mello et al., 2010). The setup is capable of producing dynamic rupture along an inclined, frictional interface formed by two compressed quadrilateral sections of Homalite (Figure 1b). The static compressive stress  $P$ , applied to the test specimen assembly (Figure 1b), provides resolved shear and normal prestresses  $\tau_0 = P \sin \alpha \cos \alpha$  and  $\sigma_0 = P \cos^2 \alpha$  on the fault, where  $\alpha$  is the inclination angle of the interface, simulating tectonic stresses applied to a fault within the Earth's crust. Dynamic rupture is triggered through a local pressure release provided by a rapid expansion of a NiCr wire filament due to an electrical discharge.

We have developed a new technique to image the full-field evolution of dynamic ruptures (Rubino et al., 2017). The development of this technique, and its application to Homalite interfaces, constitutes a milestone towards characterizing the behavior of dynamic ruptures along interfaces with rock gouge. The new technique combines ultra-high-speed digital photography (with frame rates of the order of 1-2 million frames per second) with digital image correlation (Sutton et al., 2009; Rubino et al., 2015a; Rubino et al., 2015b) to produce full-field time histories of particle motions (Figure 1). The displacement maps are processed to obtain full-field maps of displacement rates, strains, and stresses.

To illustrate the potential of this novel experimental technique, Figure 1 shows experimentally obtained snapshots of full-field displacement, fault-parallel velocity and shear stress caused by a supershear rupture in our traditional experimental setup with a purely Homalite interface. This test was performed with an applied load of  $P = 23$  MPa and an inclination angle of  $\alpha = 29^\circ$ . We clearly see the Mach cones associated with the supershear rupture propagation.

## **Detailed local measurements of friction consistent with rate-and-state and flash heating formulations**

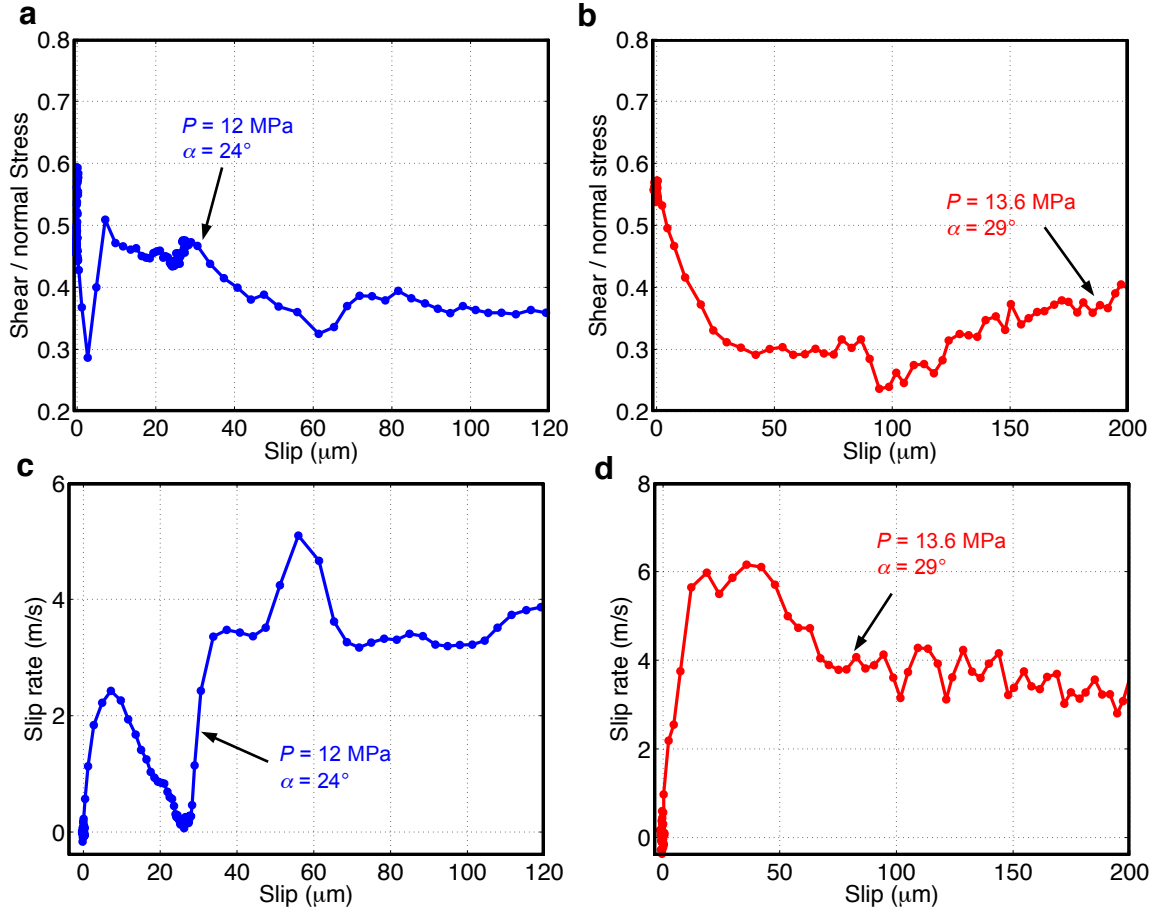
Using the newly developed technique, we have imaged experimentally the dynamic variation of friction during spontaneous dynamic rupture along Homalite interfaces (Rubino et al., 2017; Rosakis et al., 2017; Rosakis et al., 2016; Rubino et al., 2016). To characterize dynamic friction,



**Figure 1:** Imaging earthquakes in the laboratory using the ultra-high-speed digital image correlation (DIC) technique (Rubino et al., 2017a). (a-b) Earthquakes are mimicked in the laboratory by dynamic ruptures propagating along an inclined frictional interface, under the applied shear and normal prestresses. The level of prestress is controlled by the applied far-field loading  $P$  and interface inclination angle  $\alpha$ . Part of the interface has a speckled pattern applied for the subsequent analysis. The picture of the San Andreas Fault, shown for visual comparison in panel (a), is modified from [www.sanandreasfault.org](http://www.sanandreasfault.org) (Copyright (c) David K. Lynch). (c-e) The full-field time histories of displacements, velocities and stresses are experimentally obtained by capturing sequences of images with ultra-high-speed photography, and processing them with pattern-matching algorithms and highly tailored analysis. The case shown is for  $P = 23$  MPa and  $\alpha = 29^\circ$ .

we track the temporal evolution of normal and shear stress along the fault as well as slip and slip rate. Slip and slip-rate functions are obtained by subtracting fault-parallel displacements and velocities just above and below the interface. Strain evolution is computed by spatial differentiation of the time series of the displacement maps. Stress fields are determined from the strain fields using the known linear elastic constitutive properties for Homalite-100 (Young's modulus  $E = 5.3$  GPa and Poisson's ratio  $\nu = 0.35$ ).

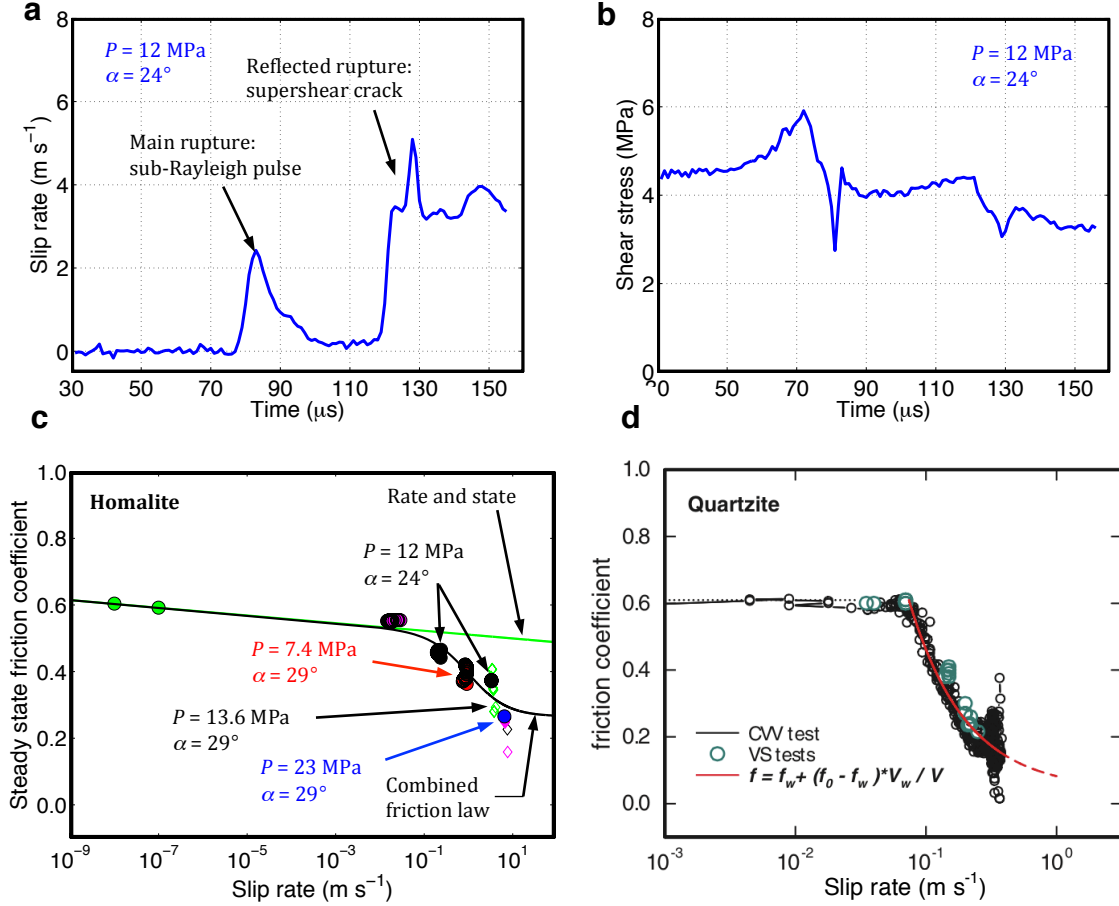
An example of the experimentally measured evolution of friction vs. slip is given in Figure 2a and 2b for two different ruptures. The experiment shown in Figure 2a features a pulse-like rupture followed by a supershear crack and it is obtained for a load of  $P = 12$  MPa and  $\alpha = 24^\circ$ . The supershear crack is produced by the interaction of the sub-Rayleigh pulse with the sample boundary. The measurement shown in Figure 2b features a supershear crack. The two experimental ruptures have different dependence of friction on slip, indicating that friction cannot be described by a purely slip-dependent law. These two ruptures are characterized by a very different slip-rate evolution as shown in Figure 2c and 2d. The slip-rate and friction time history are given in Figure 3a-b, for the case of  $P = 12$  MPa and  $\alpha = 24^\circ$ .



**Figure 2:** (a-b) Evolution of friction (= shear to normal stress ratio during slip) with slip on the interface for a point at the center of the field of view shown in Fig. 2b. The two experimental ruptures have different dependence of friction on slip, indicating that the friction cannot be described by a purely slip-dependent law. (c-d) Evolution of slip rate vs. slip for the same ruptures. The two ruptures are characterized by significantly different slip-rate histories, which result in different friction at any given value of slip.

Our experimental measurements demonstrate that friction evolution with slip velocity is consistent with the combined rate-and-state and flash-heating weakening formulation (Figure 3c; Rice, 2006; Beeler et al., 2008; Goldsby and Tullis, 2011; Thomas et al., 2014). These measurements are unique in that they are performed locally during a spontaneously evolving rupture, rather than obtained from a combination of friction experiments where different sliding velocities are imposed from the testing apparatus and assumed to be uniform over the slipping surface. We find evidence for initial strengthening with slip rate (not shown here), as would be predicted by the direct effect of rate-and-state friction, followed by weakening. The significant weakening measured in our experiments cannot be explained with standard, logarithmic rate-and-state formulations that generally result in mild friction changes. However, our steady-state measurements (Figure 3c) indicate that a combined formulation of low-velocity rate-and-state friction and high-velocity flash heating matches the results quite well (Rubino et al., 2017). There is a remarkable qualitative similarity between our measurements obtained on a polymer and those obtained on quartzite rock (Figure 3c and 3d; Goldsby and Tullis, 2011).

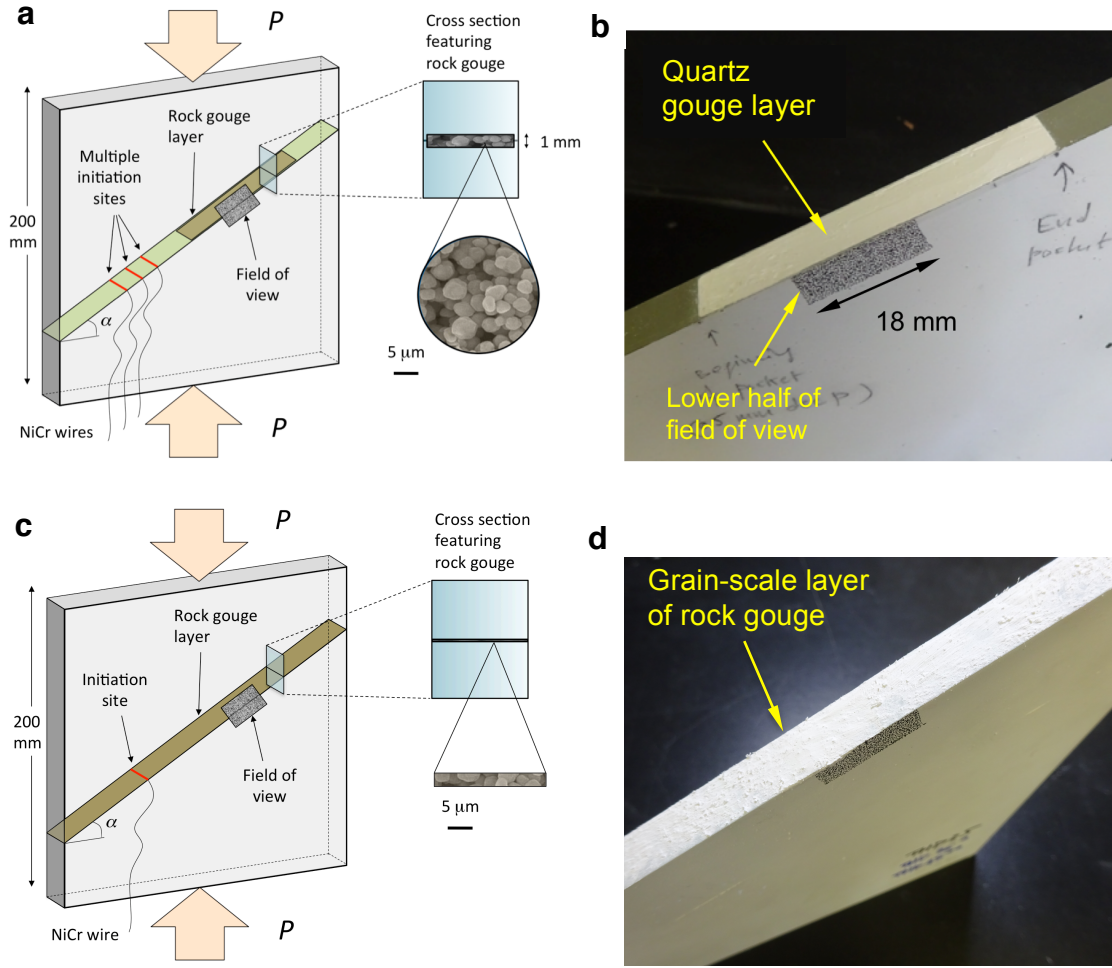
We are currently using this technique to explore the effects of the presence of rock gouge on the interface by quantifying dynamic friction evolution together with slip and slip rate.



**Figure 3:** Quantifying rupture evolution in laboratory experiments and steady-state measurements of friction (modified from Rubino et al., 2017a). (a) Slip rate and (b) shear stress time histories for an experiment exhibiting a sub-Rayleigh pulse-like rupture propagating first, followed by a supershear crack-like rupture induced by slip interaction with the sample boundary (experimental conditions  $P = 12$  MPa and  $\alpha = 24^\circ$ ). (c) Experimental measurements of steady-state friction coefficient for sustained slip at a given slip rate, based on multiple ruptures with different prestress conditions (all colored symbols except for green dots). Green dots are low-velocity measurements obtained in collaboration with Kilgore, Beeler, and Lu in a different apparatus and reported in Lu (2009). Fits to low-slip data with the standard rate-and-state friction formulation (green curve) and all data points with the combined formulation of rate-and-state friction enhanced by flash heating (black curve) demonstrate that our steady-state measurements are consistent with the combined formulation. (d) Experimental measurements of dynamic friction on quartzite samples (Goldsby and Tullis, 2011), showing qualitatively similar behavior for rocks. Note the different horizontal scale for the two plots.

### Dynamic rupture experiments along interfaces with rock gouge

The majority of the experimental studies in our lab have been conducted on analog materials such as Homalite. A linear elastic material under the strain rates of interest, Homalite has wave-mediated stress transfer through the bulk qualitatively similar to rocks. Indeed, the experiments feature slip rates in the m/s range (Figure 3), similar to those encountered in the field. Furthermore, one of the important advantages of using Homalite as the analog material is its low



**Figure 4:** Top row: Specimen configuration featuring a mm-thick layer of quartz rock gouge along the interface of two Homalite plates. (a) A channel is manufactured along a portion of the interface on both mating sides of the Homalite plates (colored in brown). The inset shows a cross section of the channel with rock gouge. The channel contains the rock gouge material during preloading and prevents it from spilling over during rupture propagation. Multiple embedded wires allow us to trigger several ruptures in the same sample, accumulate slip over the repeated events, and study the evolution in response of the gouge layer. (b) Picture of the bottom half of the sample showing the quartz gouge insert and the location of lower half of the field of view. Bottom row: Specimen featuring a thin, grain-scale layer of rock gouge along the interface of two Homalite plates. This arrangement did not result in a successful configuration in generating ruptures along gouge interfaces (see text). (c) Quartz gouge is glued to both mating sides of the Homalite interface to mimic bare-rock interfaces. (d) Picture of the bottom half of the sample with the thin layer of gouge glued on the interface.

shear modulus ( $\mu_H = 1.4$  GPa) compared to that of rocks ( $\mu_R \approx 30$  GPa). Characteristic rupture length scales, such as the critical crack size and nucleation size, are proportional to the shear modulus of the host material. So, assuming similar friction behavior, ruptures propagating in Homalite have smaller characteristic rupture length scales compared to rocks by a factor of  $\mu_R/\mu_H \approx 20$ . Indeed, our critical crack sizes range from millimeters to low centimeters for the range of experimental conditions that we use, allowing us to observe well-developed ruptures in Homalite

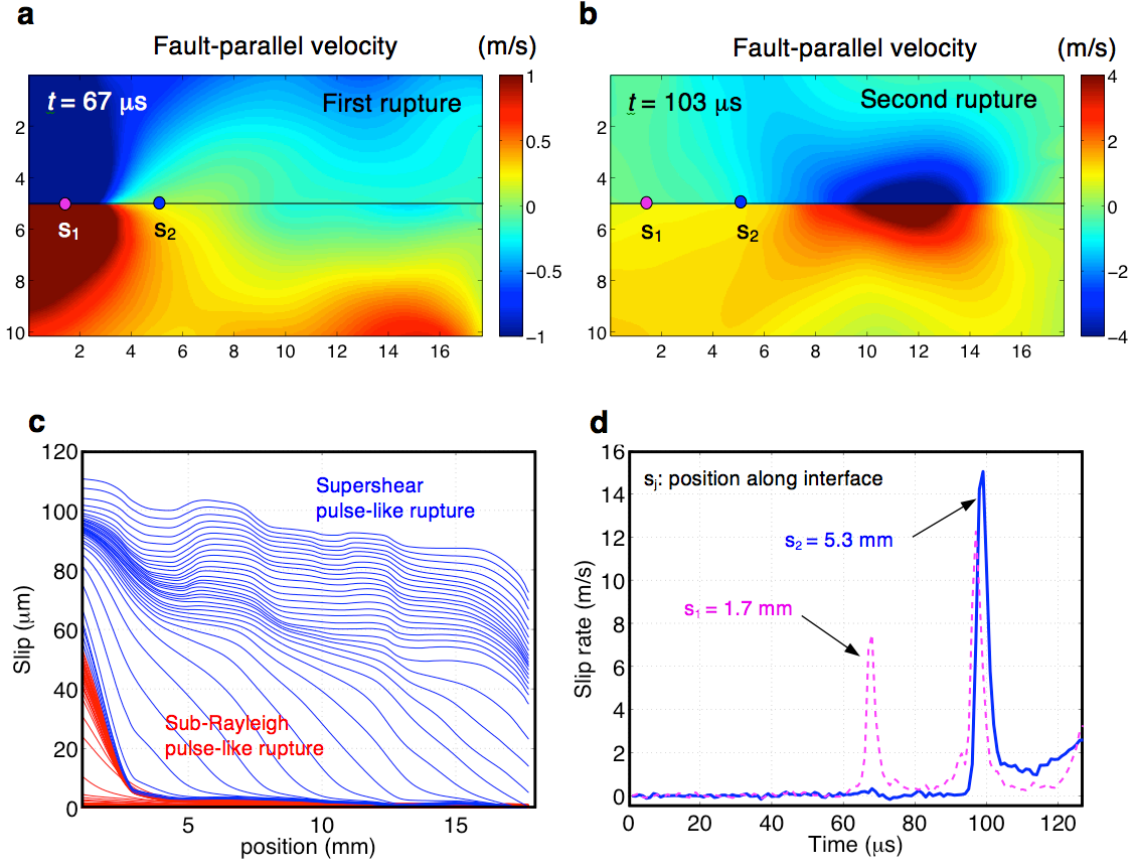
specimens of 200-mm size (e.g., Lu et al., 2009). At the same time, the unique two-meter rock experimental setup at USGS (Dieterich, 1981; Okubo and Dieterich, 1984; Beeler et al. 2012; McLaskey and Kilgore, 2013; McLaskey et al., 2014) has the nucleation size of the order of 1 m with the currently used surface preparation, leaving only 50 cm – or half the nucleation size – on each side for spontaneous rupture propagation. Hence while the USGS setup has been indispensable for recent studies of earthquake nucleation, microseismicity, and source parameters such as stress drop and slip velocity, it currently cannot be directly used to study factors that control rupture mode or supershear transition. Previous experiments in the two-meter setup on much smoother surfaces did achieve dynamic rupture and may have turned supershear (Okubo and Dieterich, 1984). However, changing the setup to study different surfaces is quite an undertaking due to time-consuming preparation and alignment processes.

Homalite interfaces may have different evolution of friction properties from rock ones, due to differences in thermal, microstructural, chemical, and other properties. While the friction properties of Homalite are broadly similar to the typical ones for rocks, with static friction coefficients of the order of 0.6-0.7, rate-and-state properties at low slip rates (Lu, 2009), and evidence for flash heating as discussed in above section and shown in Figure 3 (Rubino et al; 2017), there may be significant differences. For example, flash-heating-like weakening reduces friction coefficients to values  $\sim 0.3$ - $0.4$  for Homalite (Figure 3c), while the values for rocks are shown to be smaller,  $\sim 0.1$ - $0.2$  (Figure 3d; Goldsby and Tullis, 2011). That begs the question: What other aspects are significantly different? Since we can now determine minute details of friction evolution during dynamic rupture, we can employ our newly developed technique to both ensure that our interfaces have frictional properties relevant to natural faults and explore the friction behavior of geomaterials.

With this USGS support, we have developed experiments to study rupture dynamics with rock-governed frictional resistance by incorporating rock gouge into the Homalite sample interface (Figure 4). Gouge, the fine-grain rock powder that results from wear along the slipping surfaces, is present in most natural faults (e.g., Chester and Chester, 1998; Reches et al., 2007). It is possible to start with initially bare rock samples and produce a layer of gouge during slip (e.g. Reches and Lockner, 2010). Laboratory experiments have found that the friction response of gouge layers ranges from rate strengthening to rate weakening (Dieterich, 1981; Tullis, 1988; Marone et al., 1990; Marone and Kilgore, 1993; Beeler et al. 1996). Rate-weakening behavior is associated with the onset of shear localization and formation of microstructures (e.g. Logan et al., 1992; Beeler et al., 1996; Marone 1998), with frictional properties changing with the microstructural evolution (Rathbun and Marone, 2013).

We have developed a sample configuration featuring a mm-thick layer of quartz gouge (Figure 4a-b). In this configuration, a 1 mm-deep channel is milled along a portion of each mating half of the Homalite specimen (colored in brown in Figure 4a), in order to contain the gouge material both during preloading and rupture propagation. A fine mist of glue is deposited on the bottom of each channel, and then each half of the specimen is pressed against quartz gouge. The excess gouge is subsequently removed by passing a razor blade over the interface (Figure 4b). We have started by employing commercially available fine-ground quartz powder available from the company U.S. Silica in a wide range of sizes (top size 5-100 microns). We have used this configuration (with grains of 5 microns top size) to produce dynamic ruptures propagating along the gouge layer and we have successfully imaged several ruptures. Note that dynamic rupture is initiated on the Homalite portion of the interface (colored in green in Figure 4a) and has a chance of developing there, before entering the portion of the interface with gouge (colored in brown). This guarantees a well-developed rupture entering the gouge layer. We have embedded several wires on the interface in order to trigger several ruptures and accumulate slip over repeating events.

We have also tested other configurations. For example, we explored the possibility of incorporating rock gouge as thin, grain-scale layer glued to the interface (Figure 4c). The



**Figure 5:** Example of multiple dynamic ruptures propagating along the mm-thick layer of quartz gouge layer embedded in a Homalite sample. The specimen configuration is shown in Figure 4a-b; the field of view is  $18 \times 11 \text{ mm}^2$ ; the experimental conditions are  $P = 15 \text{ MPa}$  and  $\alpha = 29^\circ$ . This test features two ruptures: a sub-Rayleigh pulse-like rupture propagating first but dying within the first  $\sim 4 \text{ mm}$  of the field of view, followed by a supershear rupture, also pulse-like. The second, stronger rupture is induced by interaction of the other front of first rupture with the boundary of the sample. The presence of gouge has the effect of turning crack-like ruptures into pulse-like, as Homalite interfaces would host crack-like ruptures under these loading conditions. (a-b) Snapshots of the fault-parallel velocity maps at times of  $67 \mu\text{s}$  and  $103 \mu\text{s}$  after initiation, respectively. The two snapshots capture each of the two ruptures. (c) Slip vs. position curves plotted every  $1 \mu\text{s}$ , for a total recording time of  $128 \mu\text{s}$ . Red curves cover the time interval  $0\text{--}91 \mu\text{s}$ , and blue curves  $92\text{--}128 \mu\text{s}$ . The two sets of curves correspond to the two distinct ruptures. (d) Slip rate vs. time given for two points along the interface, at a distance of  $s_1 = 1.7 \text{ mm}$  and  $s_2 = 5.3 \text{ mm}$  from the left boundary of the field, respectively. The curve at  $s_1$  shows both pulse-like ruptures, while the curve at  $s_2$  only shows the supershear rupture, as the sub-Rayleigh rupture is arrested before crossing the measurement point at  $s_2$ .

technique is as follows. First, both mating sides of the interface are sprayed with an adhesive. A thin layer of gouge is then carefully spread over the layer of adhesive. Excess gouge particles (the ones that would not adhere to the interface) are subsequently removed by a jet of compressed air. One issue with this procedure is that the glue interferes with the interface properties, as glue droplets are larger than gouge grains (Figure 4d). Another issue is that ruptures produced in this configuration are much weaker compared to the configuration of Figure 4a, as they are initiated

directly in gouge and do not have a chance to develop first (as in the configuration of Figure 4a). A variant of this technique is to spread gouge over the Homalite interface without using any adhesive. The problem with this configuration is that the specimen does not hold the load as the two mating halves slide over rolling gouge grains.

The combination of rock gouge and Homalite allows us to retain the advantage in reduced critical crack sizes offered by bulk Homalite while permitting us to study more realistic interfaces. Using our newly developed technique to image full-field dynamic ruptures (described above), we have started to explore rupture behavior on interfaces with rock gouge. In particular, we are studying whether the rock-gouge interfaces exhibit the pulse-like to crack-like rupture mode change with increasing prestress, as observed in Homalite. Since flash heating in rocks has been shown to reduce the asymptotic dynamic values of the friction coefficient even more than in Homalite, to values of  $\sim 0.1$ - $0.2$  (Goldsby and Tullis, 2011), we expect that the interfaces with rock gouge will produce pulse-like ruptures for even lower shear prestresses than the Homalite interfaces. Our initial experimental observations have shown the crack-like to pulse-like transition for the rock-gouge interfaces. In the example shown in Figure 5, dynamic rupture is initiated under the experimental conditions:  $P = 15$  MPa and  $\alpha = 29^\circ$ . From previous experience (e.g. Lu et al. 2007; Mello et al., 2010), we know that these conditions would lead to a supershear crack-like rupture in Homalite. Yet, the first rupture entering the field of view (in the gouge patch) is a weak sub-Rayleigh pulse-like rupture, which dies within the first  $\sim 4$  mm of the imaging window. This behavior is evidenced by the characteristic full-field pattern of the fault-parallel velocity (Figure 5a), by the slip vs. position plot (Figure 5c), and by the slip rate time-history (Figure 5d). The sub-Rayleigh pulse (Figure 5a) is subsequently followed by a supershear pulse (Figure 5b), resulting by the interaction of the main rupture with the specimen boundary. The second, more vigorous rupture propagates through the entire size of the imaging area. Under these experimental conditions on Homalite interfaces, we would expect also the second rupture to be a supershear crack. However, the slip vs. position plot (Figure 5c) and the slip-rate time history (Figure 5d) confirm that the second rupture is also a pulse. This is an important effect due to the presence of gouge along the interface.

We have also successfully produced multiple ruptures along the same, evolving, gouge interface by means of multiple initiation sites (as shown in Figure 4a). Our measurements indicate that repeated ruptures result in more dynamic weakening of the gouge interface compared to Homalite. The dynamic friction along a gouge interface drops to  $\sim 0.16$  (not shown here), consistent with the measurements of Goldsby and Tullis on quartzite (Figure 3d). We plan to cover a broader range of experimental parameters, and then we will use the experimental results together with flash-heating theories to infer the dynamic friction properties, as in our prior studies with Homalite.

One important experimental parameter in tests with gouge is the grain size. Natural gouge from the shear zones of exhumed faults has a median by weight grain size of  $1\ \mu\text{m}$  (e.g., Chester et al., 2005). In laboratory experiments, the grain size is typically in the range of tens to hundreds of microns (e.g. Dieterich, 1981; Marone and Scholz 1989; Beeler et al., 1996). Synthetic gouge employed in the laboratory can be obtained by grinding natural rocks and sieving the powder to extract a range of grain sizes. We have started by using commercially available fine-ground quartz powder from the U.S. Silica company in the smallest available top sizes of 5 microns, and we will continue, pending new USGS award, by using larger sizes such as 10 and 15 microns. The powder with the 5 micron top size has the median particle size of  $\sim 2$  microns. These values are close to the median values in natural faults as well as to the average roughness of our Homalite surfaces which is  $\sim 5$  microns (Lu et al., 2010). This is important since the layer of gouge grains controls the roughness of the experimental interface. The roughness, in turn, would likely control the characteristic slip distance of the rate-and-state and flash-heating response of the interface, and hence cannot be too large, as we would like to be able to observe the evolved behavior of the interface for slips of the order of several tens of microns. Pending new USGS

award, we will study the effect of different grain sizes and size distributions of the rock gouge on the dynamic rupture properties and friction response of the experimental interfaces.

To summarize, introducing quartz gouge has enabled us to produce dynamic ruptures along interfaces controlled by frictional properties relevant to real faults, while keeping Homalite in the bulk allows us to still have spontaneous ruptures with small characteristic length scales. The development of a successful experimental configuration of Homalite samples enriched with rock gouge motivates us to continue exploring the effect of gouge on key rupture phenomena such as pulse-like vs. crack-like rupture behavior, as well as to quantify dynamic friction using the approach presented above. We expect that enriching the Homalite interface with rock gouge will result in amplifying flash-heating effects.

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